Kink Behavior of Central Open Flux Responsible for Helicity Injection Current Drive of the HIST Spheromak and ST Plasmas

M. Nagata, H. Hasegwa, K. Kawami, T. Takamiya, Y. Kagei
N. Fukumoto and T. Uyama
Department of Electrical Engineering, University of Hyogo

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  (Comparison between Spk and ST, Formation and sustainment of flipped ST)
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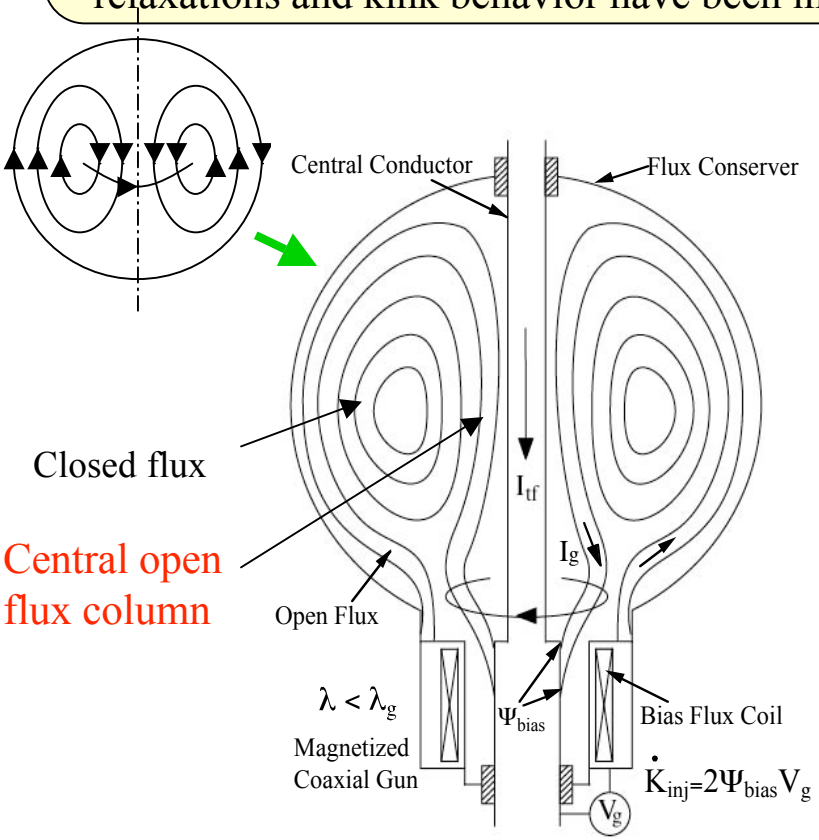
In collaboration with S. Masamune, Kyoto Inst. of Tech. and M. Katsurai, U of Tokyo

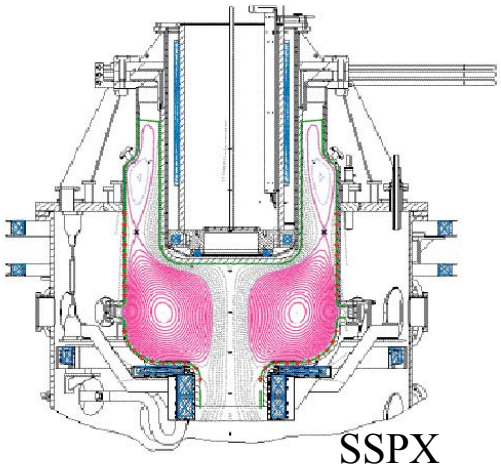
The university name was changed from Himeji Inst. of Tech..

To Study Helicity Injection Current Drive and the Underlying Relaxation Physics

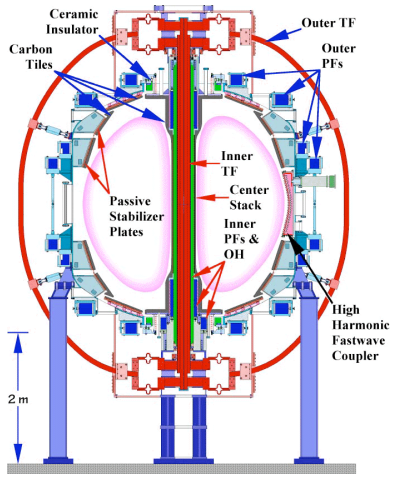
Coaxial helicity injection (CHI) technique was introduced to classical spheromaks and then spherical tokamaks to sustain a plasma current in steady-state. The ability of CHI to drive a current has been examined in many spheromak/ST devices and also various kinds of MHD relaxations and kink behavior have been interestingly observed.



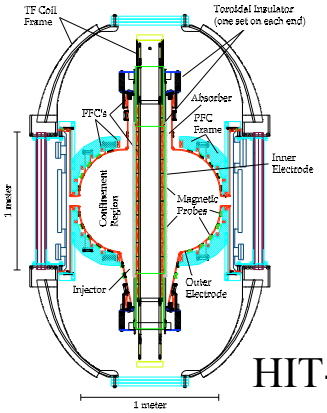
Magnetized coaxial plasma gun (MCPG)



SSPX



NSTX

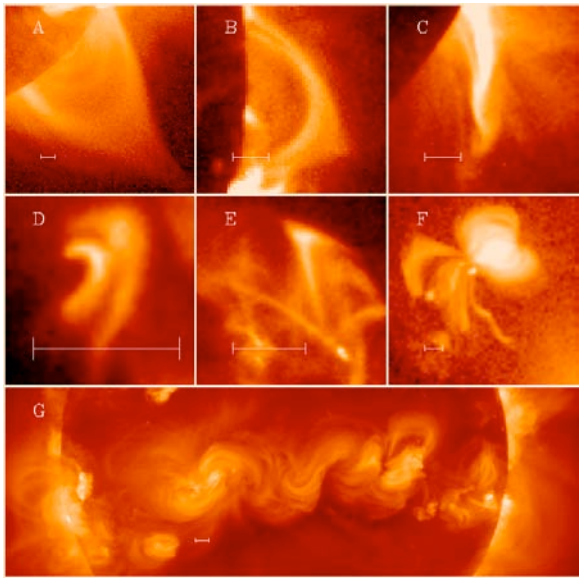


HIT-II

HIST

Close Analogy between Gun-Spheromak and Astrophysical Plasmas

Solar flares



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Robust kink behavior created by MCPG

HIST

Hsu and Bellan、 PRL

- Common self-organization phenomena are observed in both laboratory and space plasmas

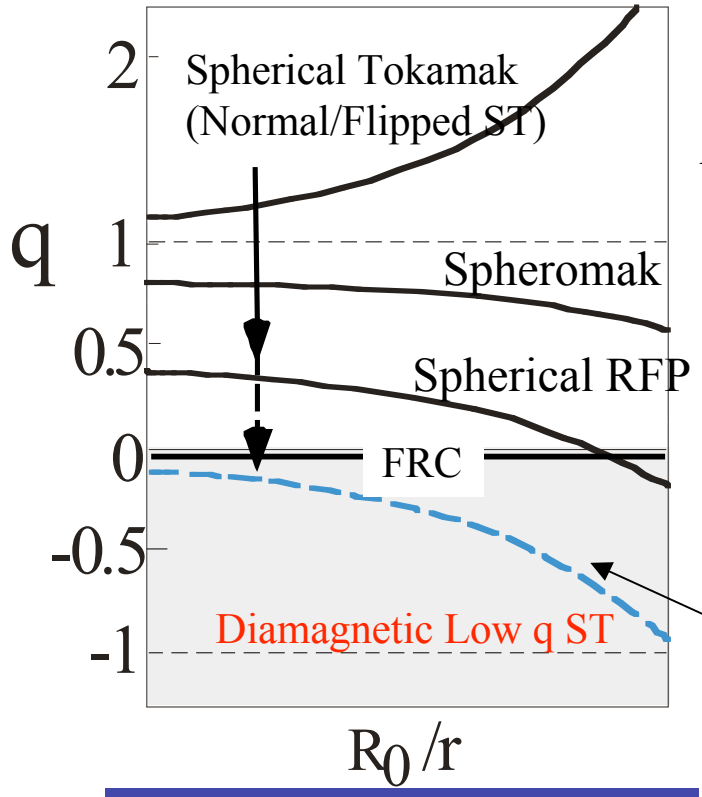
  Plasmoid ejection, Helical kink, Magnetic reconnection, Rotation

- Laboratory experiments using the MCPG help us understand the solar and astrophysical relaxation phenomena (Flares, accretion disk and jet dynamics).

Objectives and Major Goals

- The present purpose of coaxial helicity injection experiments on HIST is to investigate self-organization problems in plasma physics, common to the laboratory and space.
- Comprehensively understanding of the underlaying physics in the helicity driven system allows one to control dynamo activities (reduction in the relevant fluctuations), leading to the achievement of the efficient sustainment and better confinements of spheromaks, RFP's, and spherical tokamaks.

Understand Generic Properties of Self-Organization in Helicity-driven Spherical System; How to do it ?

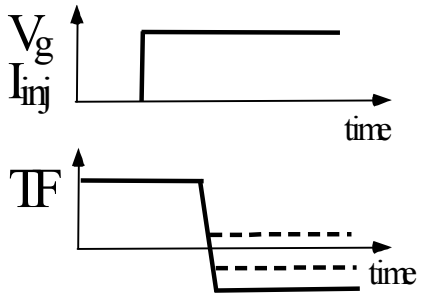


Dynamics of driven spherical system

Various Utilizations of TF coil current in the CHI scheme

A. Present works

1) Comparison study of kink behavior between SPK and ST.
2) To see what happens to ST by a rapid reversal of TF.



It is interesting to investigate whether ST plasmas collapse or survive after they pass through the rational barrier.

B. Future work

New Prediction: (see Dr. Kanki's presentation)
Formation of diamagnetic low-q ST with two fluid effect.

Increase in MHD activity, self-organized properties and large scale fluctuations

0

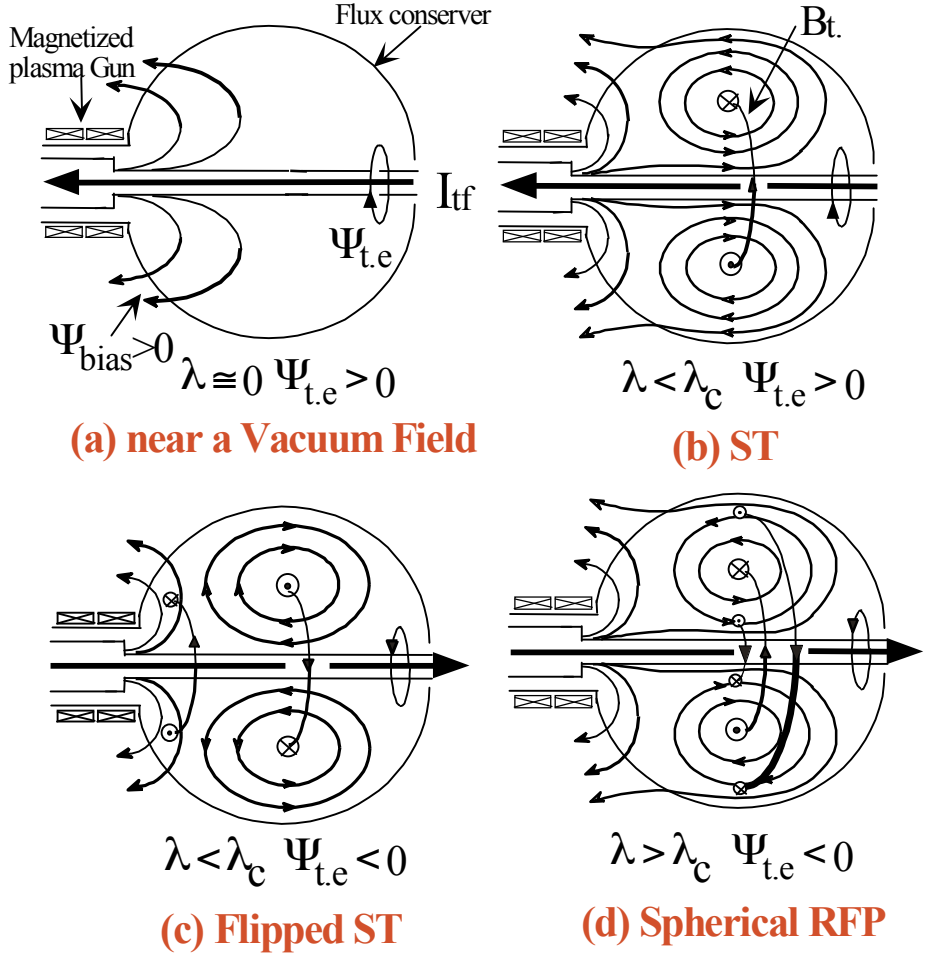
Increase in classical diffusion, stability and small scale fluctuations

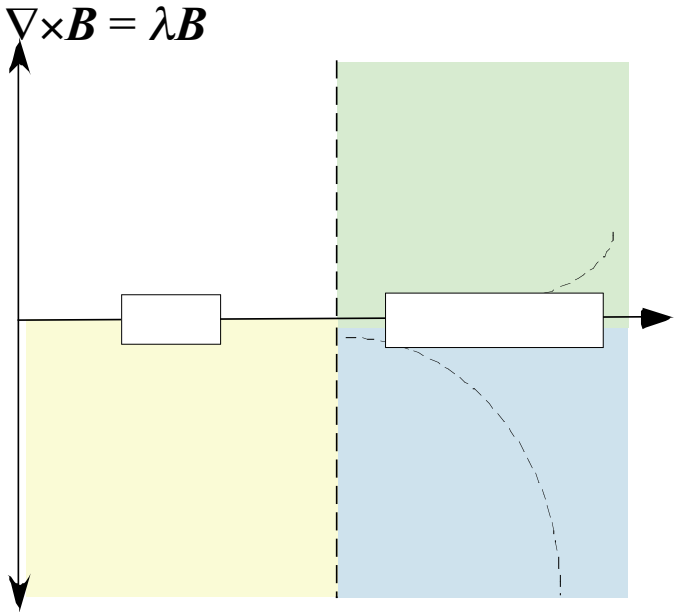
I_{tf}

S-RFP | Spheromak | High-q ST

TF coil current

Helicity-driven Relaxation Theory Predicts the Existence of Flipped ST States in the Regime of TF < 0



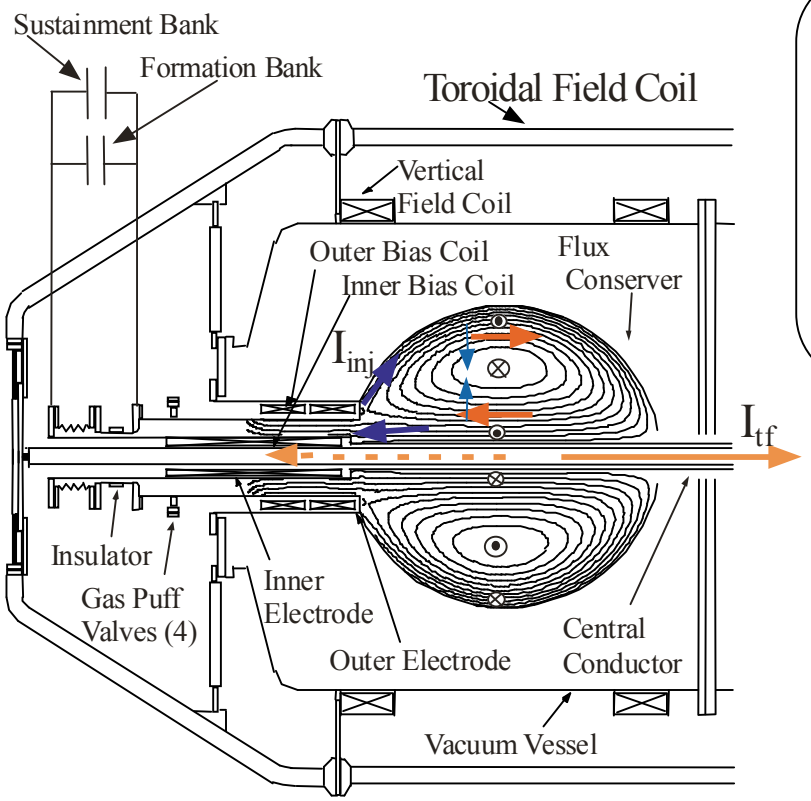


Helicity-driven relaxed states based on a single fluid MHD theory

Sequence of poloidal flux topologies of driven plasmas as λ is increased from zero to above the eigenvalue λ_c

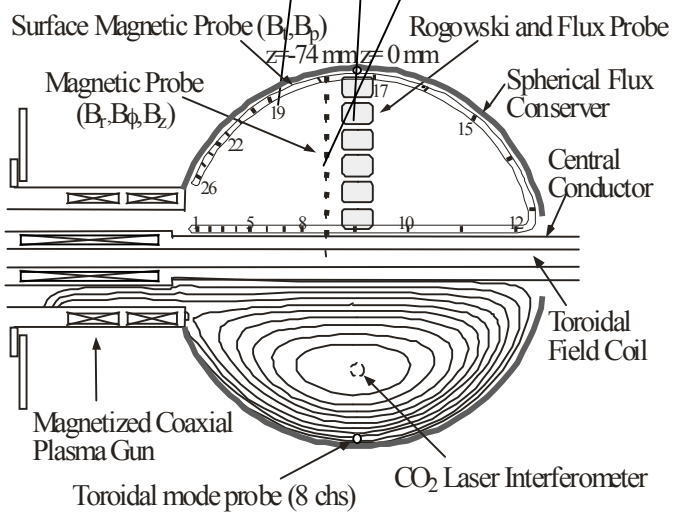
Question: How are extensions of the helicity-driven relaxation theory to two-fluid plasmas ? Then, how to approach experimentally to that region ?

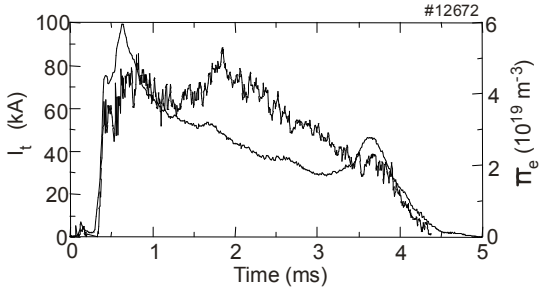
HIST and Diagnostics



Injection Current 20 kA,
Injection Voltage < 600 V
Bias Flux < 5 mWb
TF coil current < 0.3 MA

R = 0. 30 m
a = 0.24 m
A =1.25





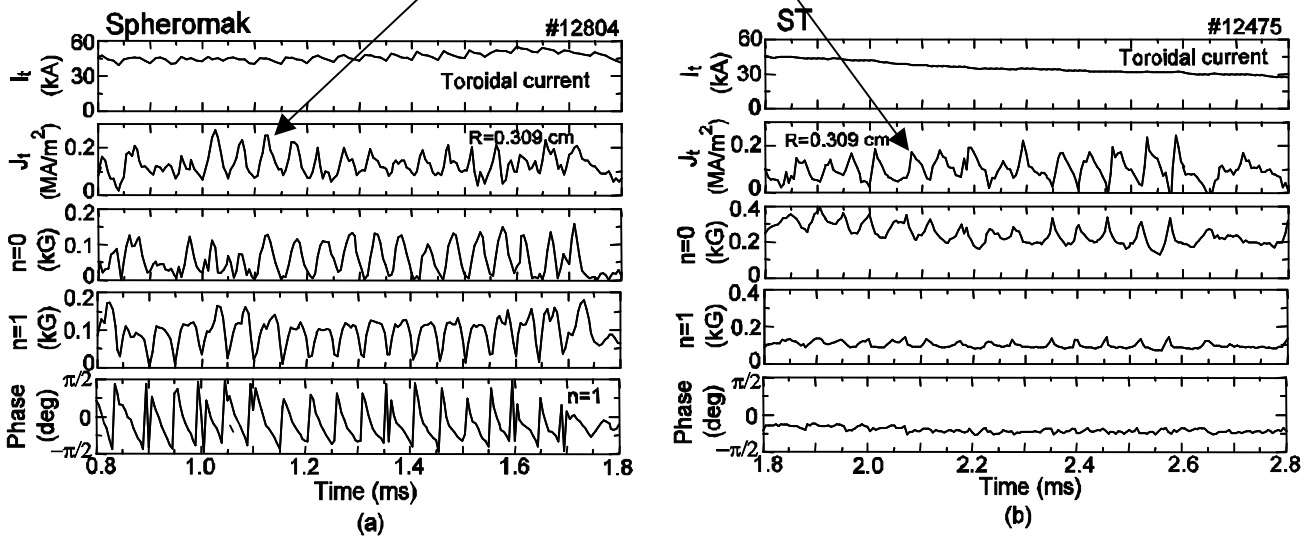
I_t < 150 kA
Δt = 4 - 8 ms
n_e = 2 - 8 x 10^{19} m^{-3}

Comparison of Magnetic Fluctuations between Spk and ST

Current generation on axis

Spheromak

Spherical Tokamak



Toroidal current

Current density on the magnetic axis

n = 0

n = 1

Phase of n =1

Large scale fluctuations

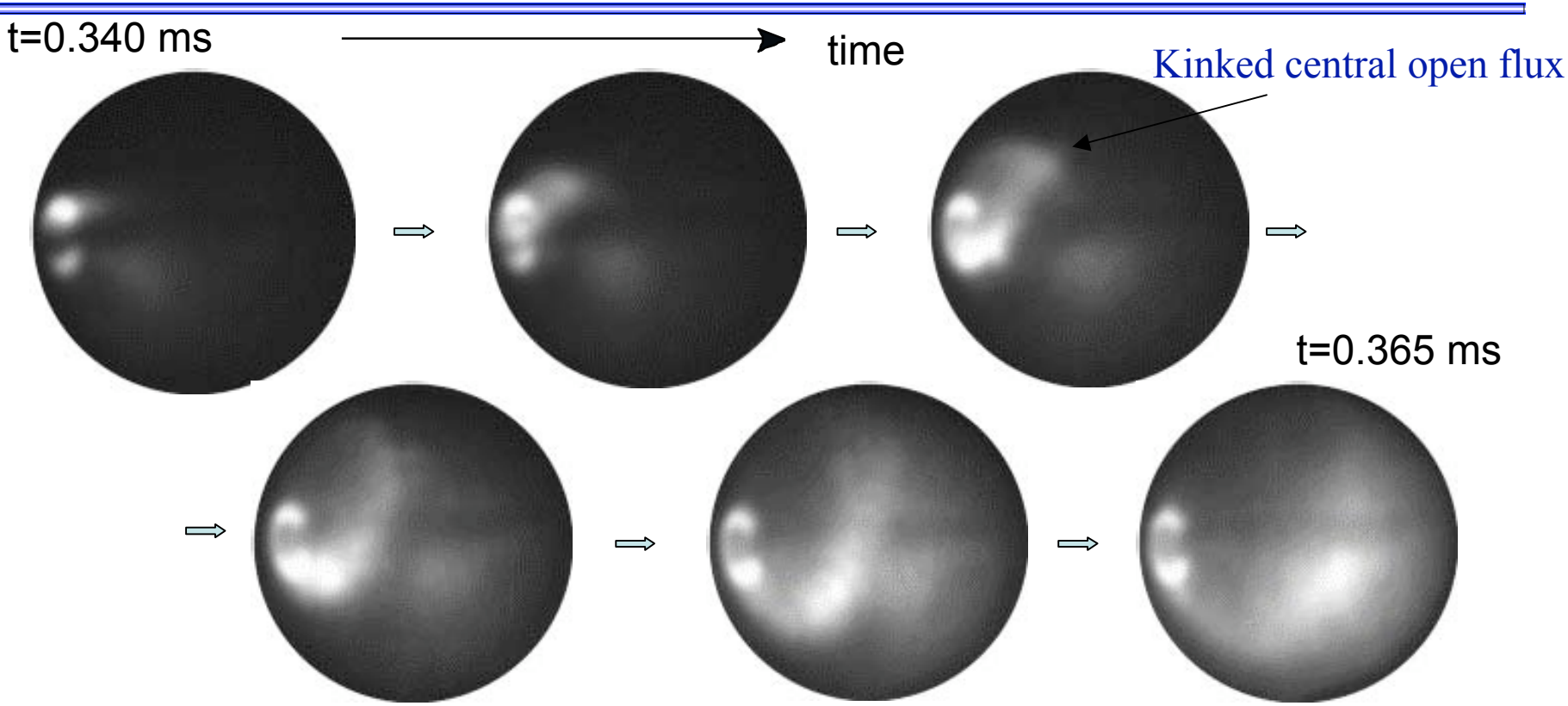
n=1 mode and its rotation

n=0 mode dominant

Small scale fluctuations

- Intermittent generation of the toroidal current at the magnetic axis was observed in both operations.
- Flux amplification/current generation in the spheromak case results from n=1 MHD activity. In the other hand, that in the ST is associated with repetitive merging of plasmoid injected from the gun which we proposed as a model of current drive so far.

Evidence of Rotating Kink Behavior Driven by MCPG



Kruskal Shafranov limit

$$\frac{2\pi^2 R_c^{\ 2} I_t}{\lambda_c R_0 I_g} > 1$$

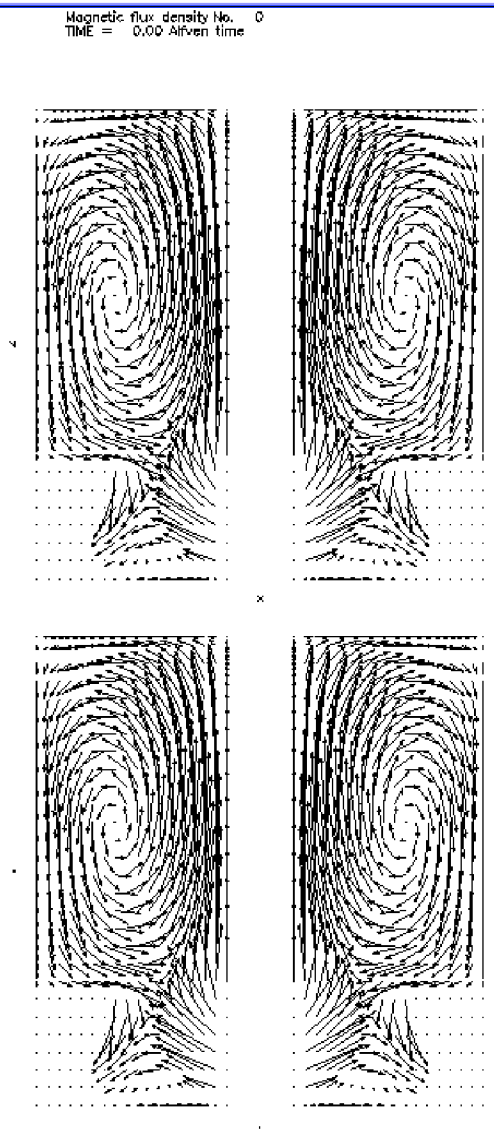
Kink mode is unstable

Exponential growth of the central open flux with the E×B toroidal rotation

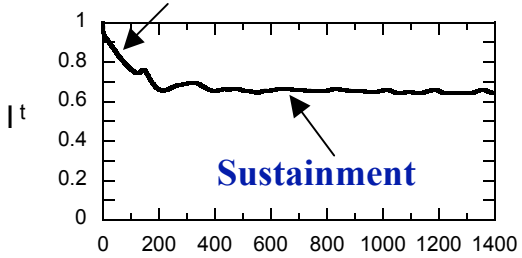
Velocity fluctuation produced by rotating kink motion.

V_Z = 30 [km/s] , V_R = 18 [km/s]

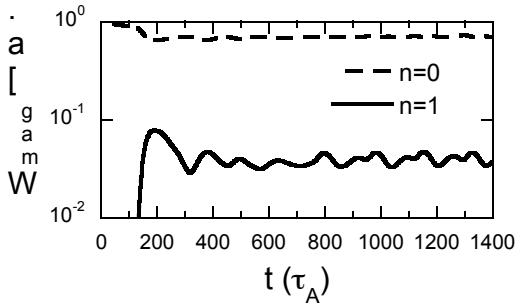
Dynamo Drive of Spheromak Exhibited by 3D MHD Simulation



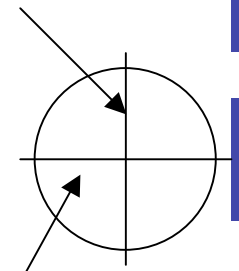
Resisitve decay



Toroidal mode n=0, 1



This simulation result is in good agreement with the experimental observation.

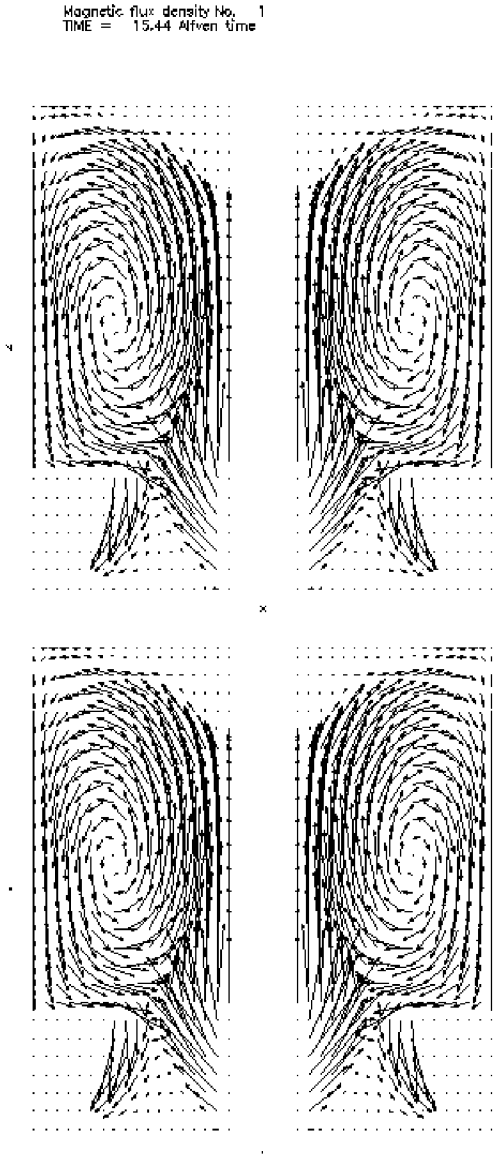


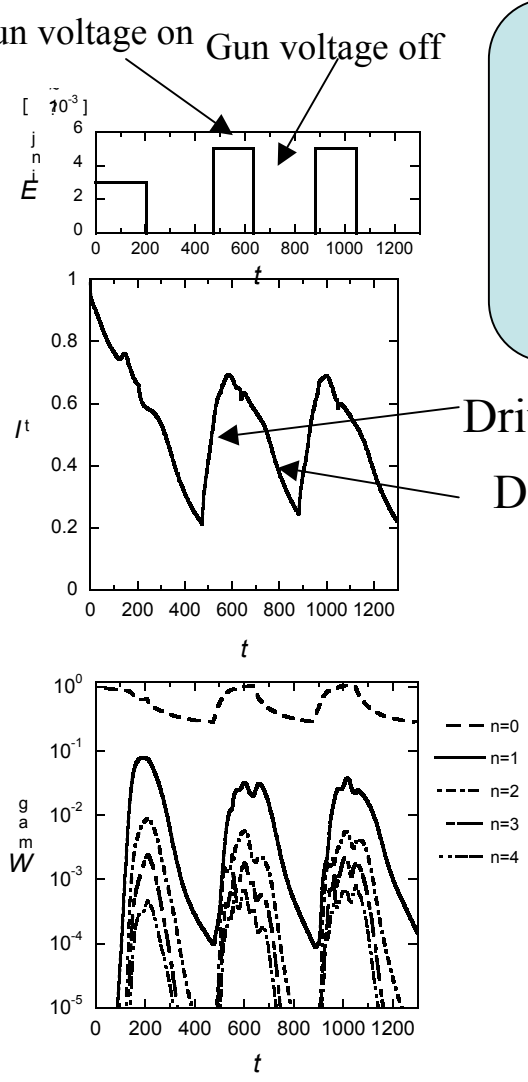
Nonlinear kink behavior of the central flux/current channel.

- Initial exponential growth of kink of the central column
- Growth, nonlinear saturation and the following relaxation of the kinked flux column produces dynamo electric field, which includes flux conversion from toroidal to poloidal.
- Closed flux surfaces are identified only as mean fields.

$$\mathbf{E}_{\text{dynamo}} = \langle \tilde{\mathbf{v}}_e \times \tilde{\mathbf{B}} \rangle$$

Multiple Pulse Operation for Improvement of Spheromak Confinement





Multi-Pulse Helicity Drive is effective for suppressing the $n = 1$ fluctuation.

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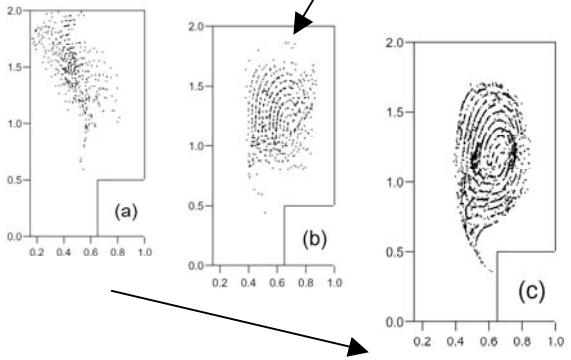
Improvement of confinement quality.

Driven phase

Decaying phase

Chaotic scattering of field lines

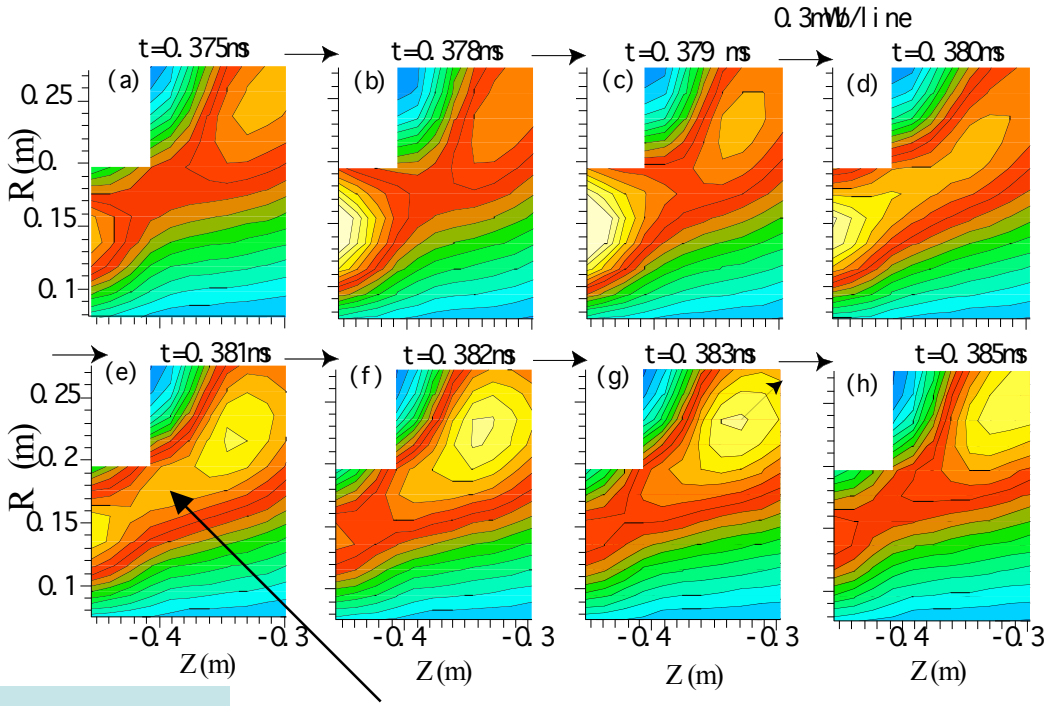


Poincare plot of magnetic field at the time when the magnetic energy in the $n = 1$ mode gets down to ~10^{-4}

↓

Closed flux surfaces are produced during the decay phase.

Plasmoid Ejection from MCPG during the Formation of ST



Stabilization of kink instability by TF

Plasmoid ejection is axisymmetric and explosive.

Magnetic reconnection point

Plasmoid ejection speed ～60km/s

- Application of a strong external TF decreases the magnetic reconnection rate so that the ratio of closed flux to the total flux in ST becomes smaller than that in SPK.
- In constract with spheromak, it becomes more important in the ST case to understand small-scale fluctuations and local features of reconnections around the X(null)-point.

Current Sustainment by Repetitive Injection and Merging of an Axisymmnetric Plasmoid from MCPG

$$2\,V_{inj}\,\Psi_{bias} = 2V_t\,\Psi_t = K/\tau_K$$

$$f_{inj}\,K_s = 2V_t\,\Psi_t = K/\tau_K$$

$$\lambda = \varepsilon\ \lambda_s$$

$$K_s = \mu^2{}_0\,\lambda_s\,a_s{}^4 I^2_{tf}/(8R_s)$$

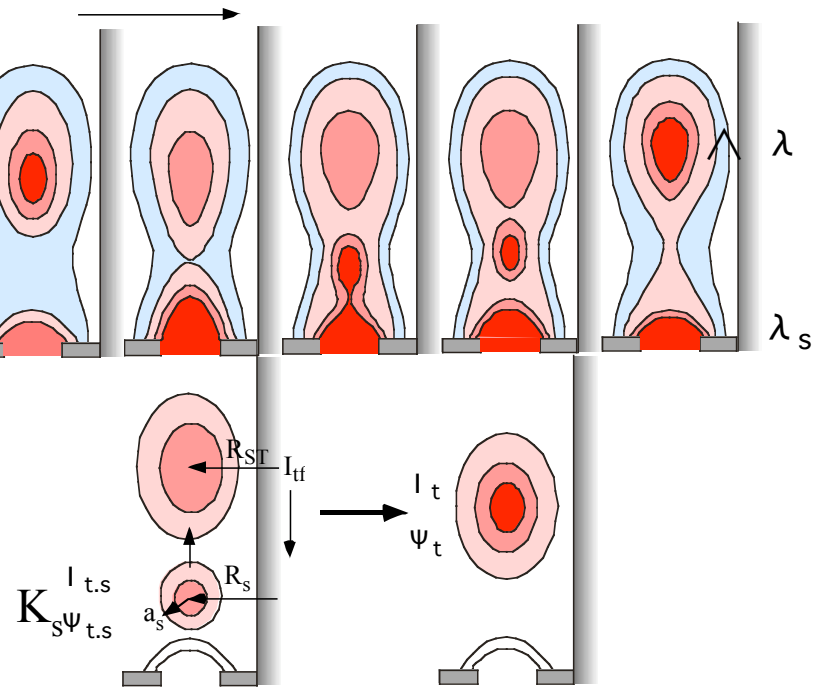
$$I_{t.s} = I_t\,\Psi_{t.s}/(\Psi_t\ \varepsilon\ )$$

$$f_{inj} = 16\ \varepsilon\ R_s V_t \Psi^2_t/(\mu^3{}_0\,a^4{}_s\,I^2_{tf}\,I_t)$$

For example, ST Reactor (R_s=1.65 m, a_s=0.25 m)

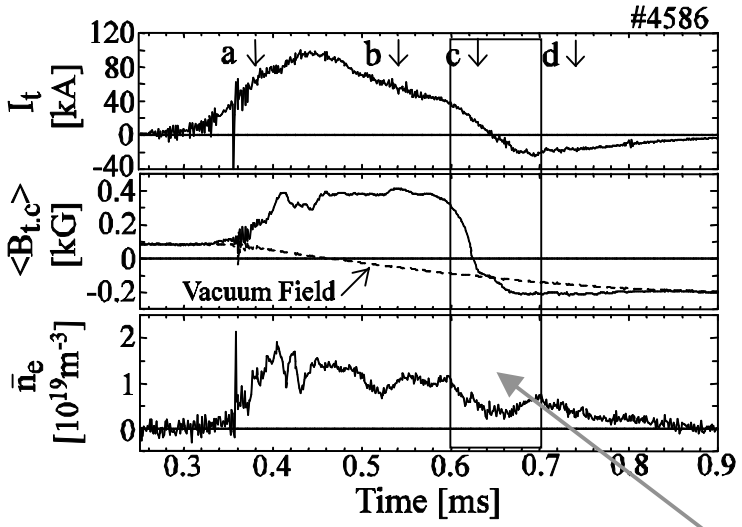
f_{inj} = 0.27 ε [s^{-1}] = 1.1 [s^{-1}] (ε =30 [%])

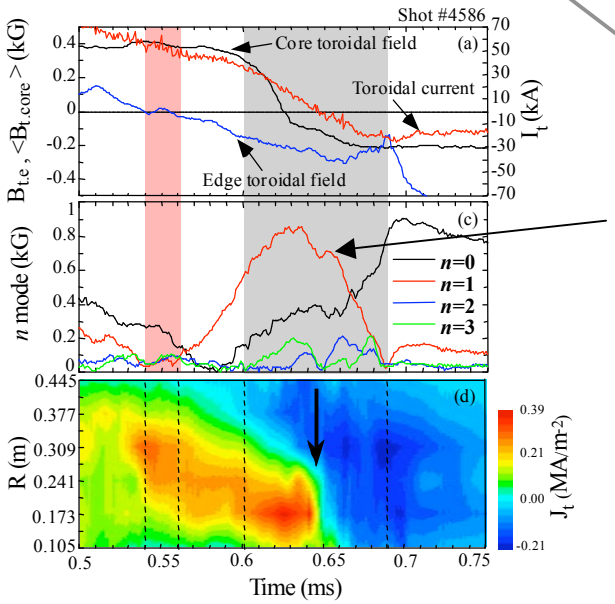
$I_{t.s}$ =1.1 [MA], $\Psi_{t.s}$ =3.3 [Wb]

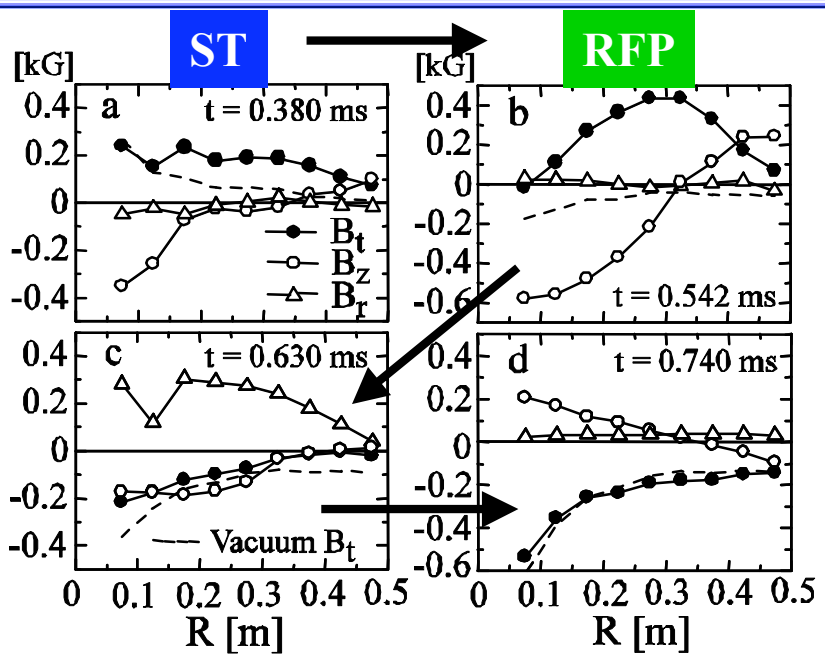


Reference: R.Farengo and T. Jarboe: Fusion Tech. Vol.**20** 407 (1991)

Observation of Self-reversal of Magnetic Fields by Reversing TF ; Relaxation from the ST toward the Flipped ST State.







Self-reversal process

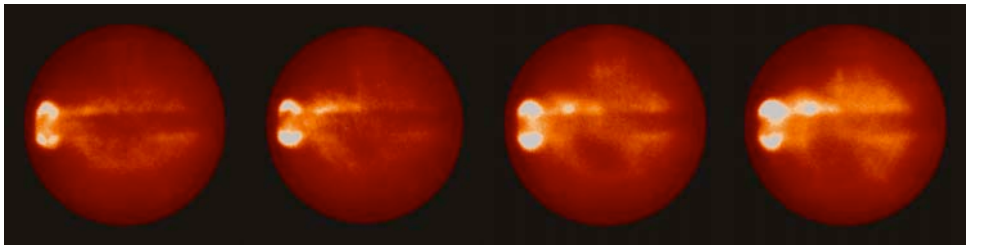
Flipped ST

Large growth of the n=1 kink mode

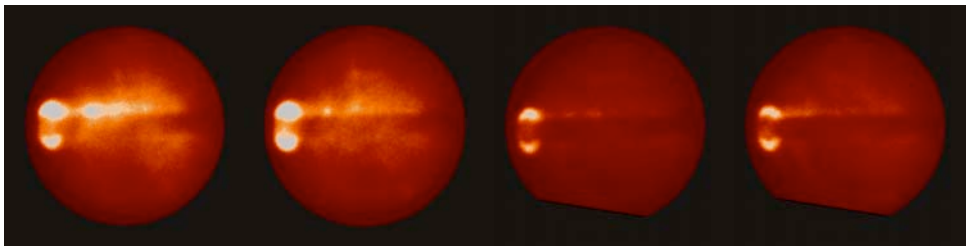
- Note that not only toroidal flux but also poloidal flux reverses the sign spontaneously during the relaxation process.

M. Nagata et al. Phys. Rev. Lett. 90, 225001 (2003)

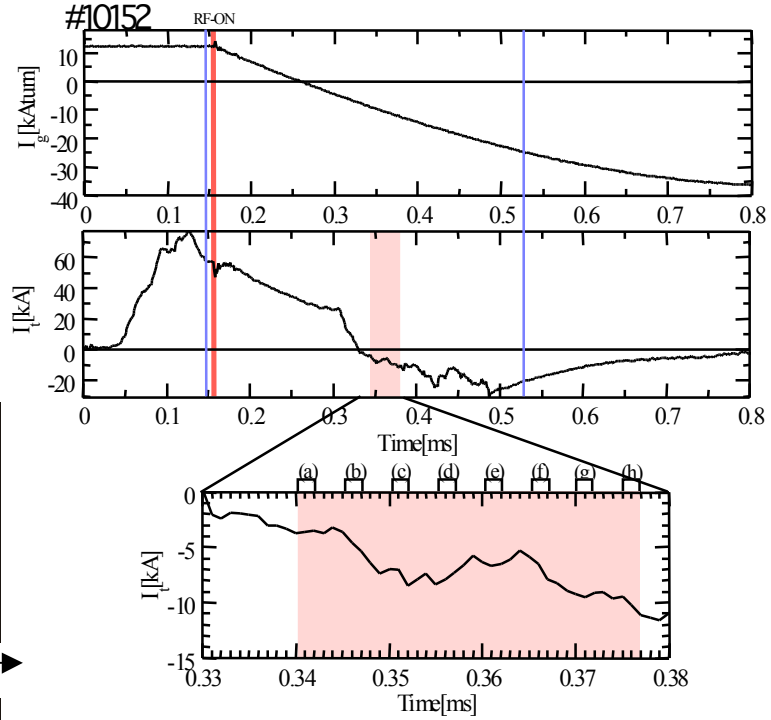
Fast Camera Images Display Kink Behavior during Self-reversal Process



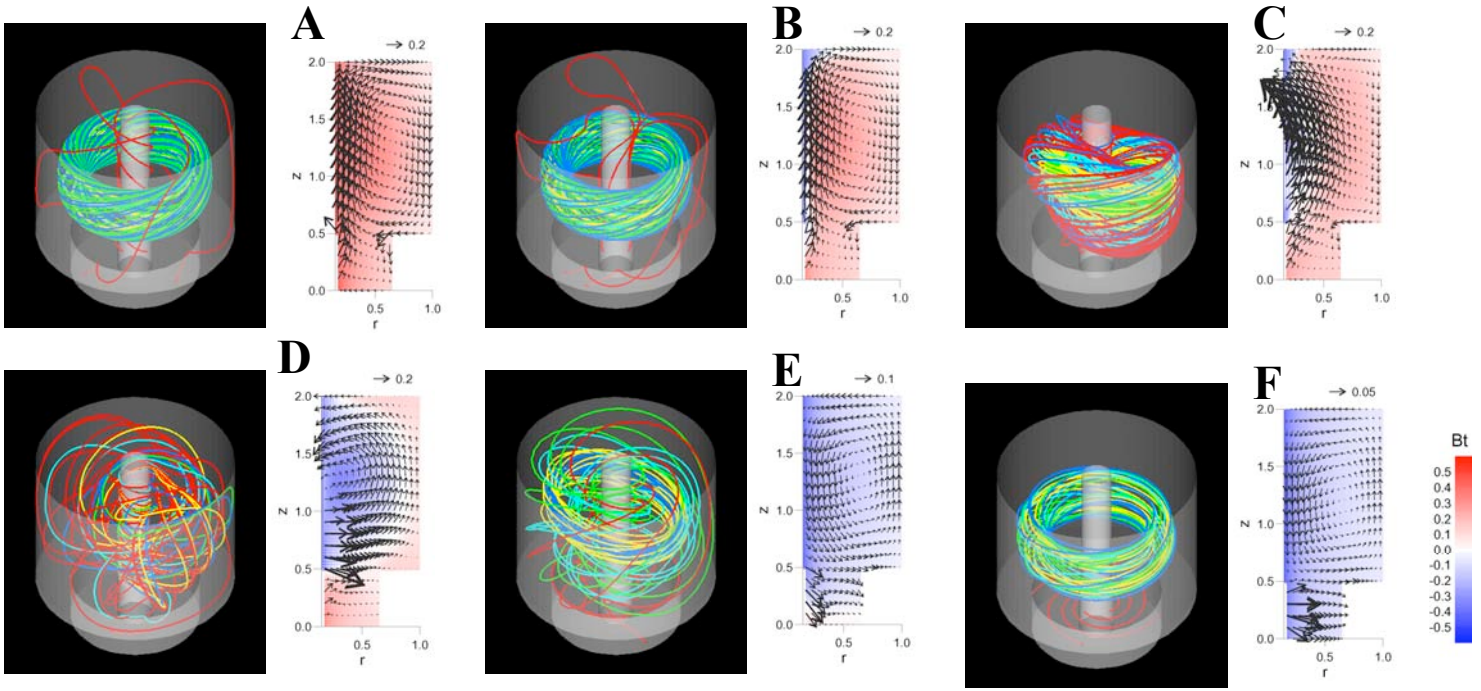
0.340ms → 0.345ms → 0.350ms → 0.355ms →



→ 0.360ms → 0.365ms → 0.370ms → 0.375ms

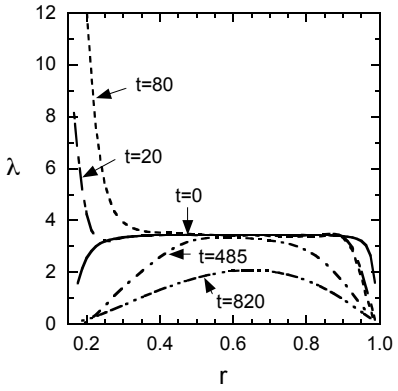


3D MHD Simulation of Self-organizing from ST to F-ST Configurations



Mgnetic reconnection between the open and closed field.
Spontaneous reversal of not only poloidal but also toroidal flux

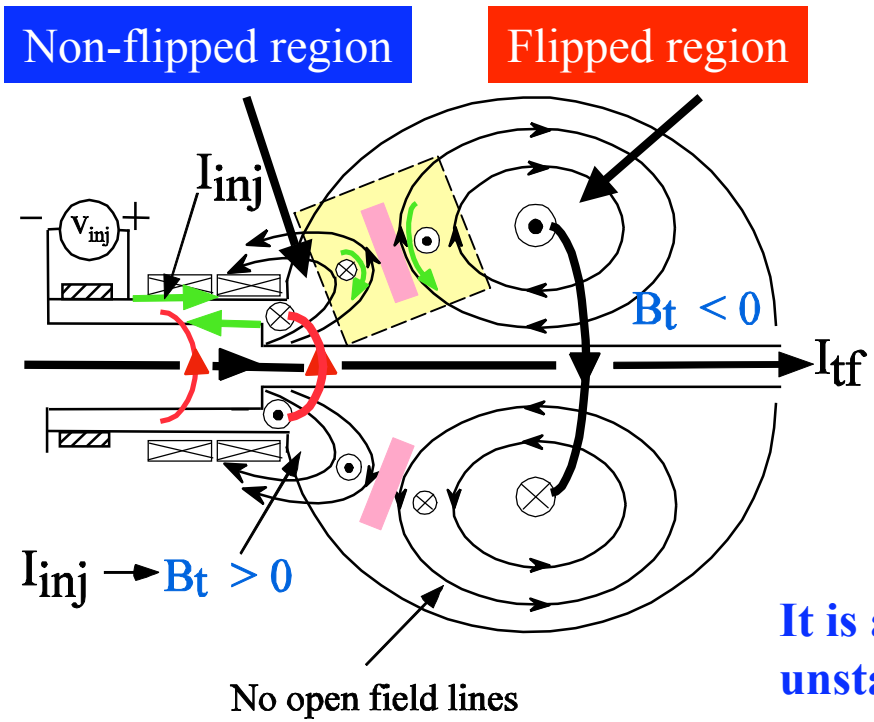
- The system relaxes to a lower energy state by rearranging current distribution. The parallel current profile λ becomes peaked.
- **Kink of the central open flux is essential to the self-reversal process.**



Y. Kagei et al. PPCF, 45, L17 (2003)

Question; Can We Sustain the Flipped ST plasmas in Spite of No Central Open Flux ?

F-ST is q>1.



The F-ST configuration is consisted of only closed flux surfaces so that it may have a better confinement quality ! ?

↓

But, the F-ST is isolated from the electrodes, so can we drive it by helicity injection?

↓

No Magnetic Reconnection ?

↓

How to produce the dynamo activity ?

↓

It is a key point to make the non-flipped field lines unstable for the kink mode.

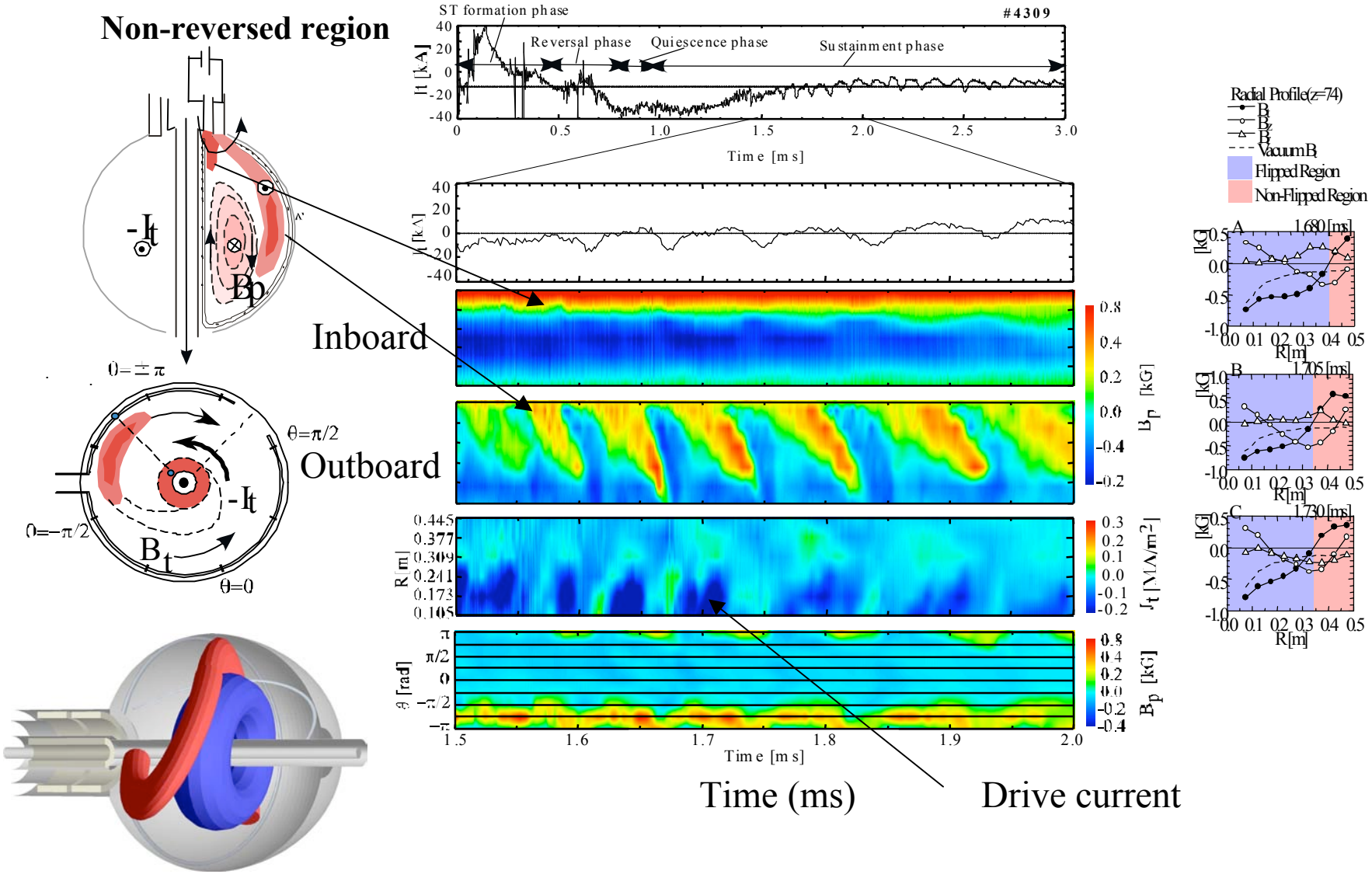
Unique magnetic field lines geometry:
B_t: opposite direction,
B_p: same direction

Kink unstable condition: $\mathbf{I_{inj} > I_{tf}}$

$\mathbf{q \sim I_{tf}/I_t > 1}$ $\mathbf{I_{inj} > I_{tf} > I_t}$.

- **Large injection current is required to sustain a large plasma current in the F-ST.**

Sustainment of F-ST Plasmas Driven by Kink Motion of Non-flipped Open Flux

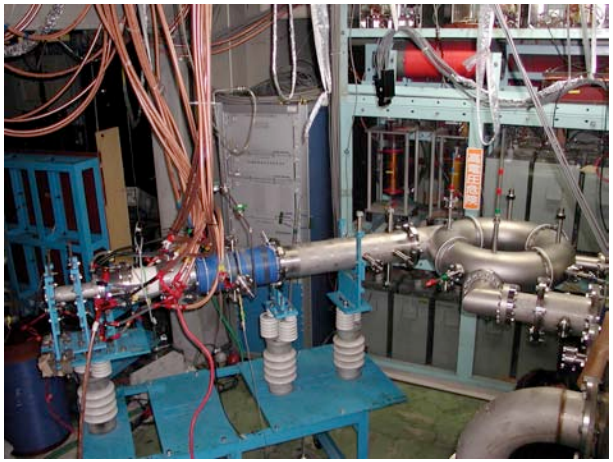


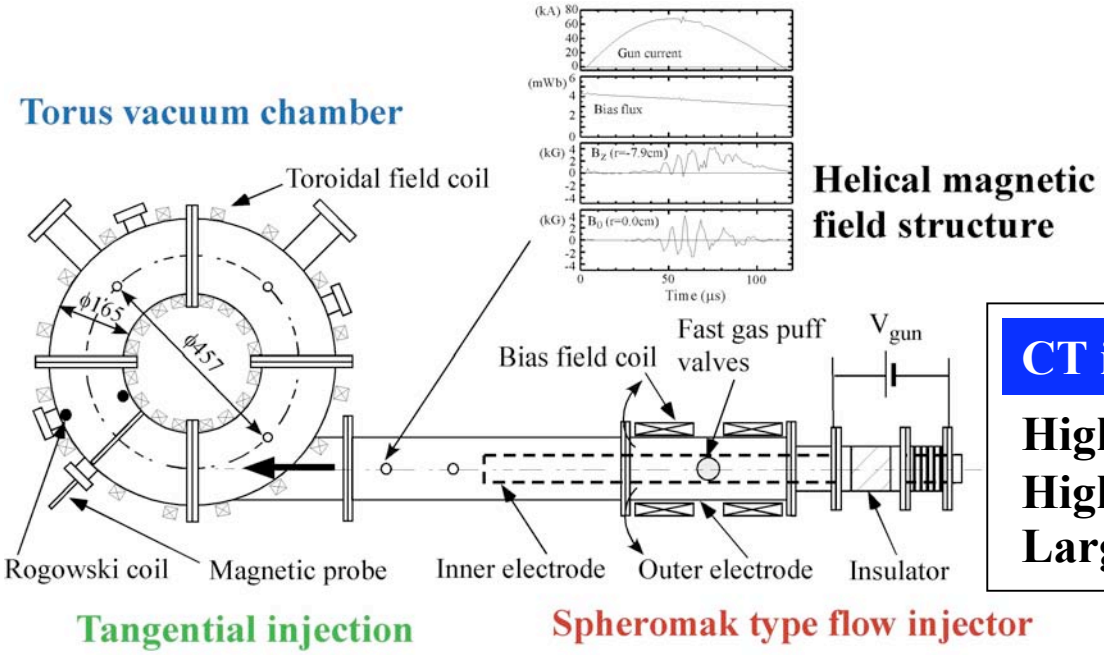
Summary and Future Plan

- **We have reviewed the MHD dynamo activities and self-organization phenomena in various helicity-driven cases (ST, Spheromak, Flipped ST, and the transition process between them).**
- **The common basic feature of the dynamo activities is the rotational kink of the open flux column, which is essential to CHI current drive mechanism.**
- **3D MHD simulation results are in good agreement with the experimental results and also determined the role of the kink behavior in dynamo drive.**
- **Local features of reconnection at X-point play an important role in the sustainment of the ST which is in contrast with non-axisymmetric and global behavior in the spheromak case.**
- **We have a plan to drive large flows by CT injection into ST plasmas to explore new helicity-driven two-fluid plasmas.**

Plan: New Experimental Setup for Relaxation Studies of Two Fluid Plasmas

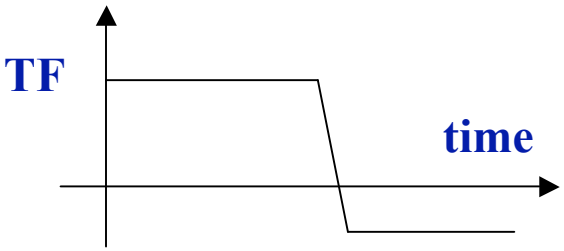
Try to produce a diamagnetic low-q tokamak by injection a CT plasma with magnetic helicity and a high speed ion flow.





CT injector

High density: 10^{21}-10^{22} m^{-3}
High speed: 100 – 300 km/s
Large Hall parameter: $h_e=\omega_{ce}\tau_e$ ~25



Injection of a high energy CT plasma into the toroidal vacuum chamber with TF coils